FIELD OF THE INVENTION

The invention relates to the testing of semiconductor wafers during manufacturing and specifically to the real-time in-line testing of semiconductor wafers during integrated circuit fabrication.

BACKGROUND OF THE INVENTION

There are numerous individual operations, or processing steps, performed, in a strictly followed sequence, on the silicon wafer in the course of manufacturing a complex integrated circuit (IC). Each such operation must be precisely controlled in order to assure that the entire fabrication process yields integrated circuits displaying the required electrical characteristics.

Frequently, failure of an individual operation is detected only after the completion of the entire, very expensive, process of IC fabrication. Due to the very high cost of advanced IC fabrication processes, such failures result in the severe financial losses to the integrated circuit manufacturer. Therefore detection of errors in the manufacturing process, immediately after their occurrence, could prevent the unnecessary continuation of the fabrication of devices which are destined to malfunction, and hence, could substantially reduce the financial losses resulting from such errors.

Process monitoring in semiconductor device manufacturing relies upon the examination of the changes which occur in certain physical and/or chemical properties of the silicon wafer upon which the semiconductor devices are fabricated. These changes may occur

1   following the various processing steps to which the silicon wafer

2   is subjected and are reflected by changes in the electrical

3   properties of the wafer.   Therefore, by monitoring selected

4   electrical properties of the silicon wafer in the course of IC

5   fabrication, an effective control over the manufacturing process

6   can be accomplished.

7   Not all of the electrical characteristics of a completed

8   integrated circuit can be predicted based on the measurements

9   performed on a partially processed wafer.   Most of the

10   characteristics however, can be predicted directly or indirectly

11   based on the investigation of the condition of the surface of the

12   silicon wafer (substrate) in the course of IC manufacture.   The

13   condition of the silicon surface is very sensitive to the outcome

14   of the individual processing steps which are applied during IC

15   manufacturing, and hence, the measurement of the electrical

16   properties of the substrate surface can be an effective tool by

17   which the monitoring of the outcome of the individual processing

18   steps can be accomplished.

19   The determination of the electrical characteristics of the

20   wafer surface typically requires physical contact with the wafer

21   surface, or the placement of a contactless probe over a stationary

22   wafer.   In the latter case an optical signal or a high electric

23   field is used to disturb equilibrium distribution of the electrons

24   in the surface and near-surface region of semiconductor.

25   Typically, the degree of departure from equilibrium is driven by

26   variations of one or more electrical characteristics of the surface

27   region, the near-surface region, and the bulk of the semiconductor.

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1   To obtain a more complete picture of the entire surface of the

2   wafer, several measurements at various points on the surface can be

3   made. Such a procedure, known as "mapping", moves the measuring

4   probe with respect to the measured material (or vice versa) over

5   the surface of specimen, stopping at a number of locations and

6   performing a measurement at each location before moving to the next

7   location. The substrate, in this procedure, does not remain in the

8   continuous motion, so consequently the applicability of such a

9   method for use in real-time in-line process monitoring is limited.

10   SUMMARY OF THE INVENTION

11   The invention relates to an apparatus and method for the real-

12   time, in-line monitoring of semiconductor wafer processing. In one

13   embodiment the apparatus includes a probe assembly located within

14   a semiconductor wafer processing line. As each wafer is carried

15   beneath or above the probe assembly by conveyor belt, robotic arm,

16   wafer chuck, or other similar device, a source of modulated light,

17   such as an LED, within the probe assembly, generates light having

18   a predetermined wavelength and frequency of modulation which then

19   impinges upon the wafer. A sensor in the probe assembly measures

20   the surface photovoltage induced by the modulated light.   The

21   signal from the sensor is sent to a computer which then uses the

22   induced surface photovoltage to determine various electrical

23   characteristics of the wafer, such as surface charge and surface

24   doping concentration, among others.

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BRIEF DESCRIPTION OF THE DRAWINGS

This invention is pointed out with particularity in the appended claims. The above and further advantages of this invention may be better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a block diagram of an embodiment of an apparatus for the real-time, in-line, electrical characterization of a semiconductor during manufacturing;

Fig. 2 is a perspective view of an embodiment of the probe assembly of the apparatus of Fig. 1 in position above a wafer transfer system;

Fig. 3 is a top perspective cutaway view of the probe assembly of Fig. 2;

Fig. 4 is a bottom perspective view of an embodiment of the sensor plate of the probe assembly of Fig. 3;

Fig. 5 is a schematic diagram of an embodiment of an electrical circuit for measuring the surface photovoltage using front wafer surface coupling;

Fig. 6a depicts a block diagram of a corona control circuit used to charge a wafer so as to generate an inversion layer at the wafer surface; Fig. 6b depicts a block diagram of the corona control circuit of Fig. 6a used to discharge a wafer;

Fig. 7 is a bottom perspective cutaway view of an embodiment of the coated sensor plate of Fig. 4 with a polyimide coating, used with sensor charging and high voltage biasing;

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1   Fig. 8 is a schematic diagram of an embodiment of a

2   preamplifier circuit used for the high voltage biasing of the wafer

3   using the sensor electrodes; and

4   Fig. 9 is a graph of front and back surface charge

5   measurements of a silicon wafer undergoing cleaning.

6   DESCRIPTION OF THE PREFERRED EMBODIMENT

7   In one embodiment, the apparatus to perform various electrical

8   characterizations makes use of the method for measuring the photo-

9   induced voltage at the surface of semiconductor materials, termed

10   the surface photovoltage (SPV), disclosed in the U.S. Patent

11   No. 4,544,887. In this method, a beam of light is directed at a

12   region of the surface of a specimen of semiconductor material and

13   the photo-induced change in electrical potential at the surface is

14   measured. The wavelength of the illuminating light beam is

15   selected to be shorter than the wavelength of light corresponding

16   to the energy gap of the semiconductor material undergoing testing.

17   The intensity of the light beam is modulated, with both the

18   intensity of the light and the frequency of modulation being

19   selected such that the resulting AC component of the induced

20   photovoltage is directly proportional to the intensity of light and

21   inversely proportional to the frequency of modulation.

22   When measured under these conditions, the AC component of the

23   surface photovoltage (SPV), designated δV_s, is proportional to the

24   reciprocal of the semiconductor space-charge capacitance, C_{sc}. When

25   the surface of the specimen is illuminated uniformly, the

26   relationship between the surface photovoltage (SPV) and the space-

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1   charge capacitance is given, at sufficiently high frequencies of

2   light modulation, by the relation:

$$\delta V_s = \frac{\Phi(1-R)}{Kf} qC_{SC}^{-1}$$

3   where Φ is the incident photon flux, R is the reflection

4   coefficient of the semiconductor specimen, f is the frequency at

5   which the light is modulated, and q is the elementary charge. The

6   constant K is equal to 4 for a square wave modulation of the light

7   intensity and is equal to 2π for sinusoidal modulation.

8   In the above referenced patent, only a uniform configuration

9   is considered in which the area of the sensor is at least the same

10 size as the semiconductor wafer and the entire area of the specimen

11 is uniformly illuminated. When only a portion of the semiconductor

12 specimen surface is coupled to the sensor, that is, when the sensor

13 is smaller than the wafer, and when the semiconductor surface

14 uniformly illuminated in that area is coupled to the sensor, the

15 surface photovoltage, δV_s, may be determined from the measured

16 signal, δV_m, according to the relationships :

17      $Re(\delta V_s) = Re(\delta V_m) \cdot (1+C_L/C_p) + Im(\delta V_m) \cdot (\omega \cdot C_p \cdot R_L)^{-1}$

18      $Im(\delta V_s) = Im(\delta V_m) \cdot (1+C_L/C_p) - Re(\delta V_m) \cdot (\omega \cdot C_p \cdot R_L)^{-1}$

19   where $Re(\delta V_s)$ and $Im(\delta V)$ are the real and imaginary components

20 of the voltage, ω is an angular frequency of light modulation, C_p

21 is the capacitance between sensor and the wafer, and C_L and R_L are

22 the   input capacitance and resistance, respectively, of the

23 electronic detection system.

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1   From the sign of the imaginary component, the conductivity

2   type may be determined. If the measurement is calibrated for a p-

3   type material, then the sign of the imaginary component will change

4   if the material is n-type.

5   Using above relationships, the depletion layer width, W_d, is

6   given by equation:

$$W_d = \frac{\epsilon}{q}\,\frac{\omega\,|Im(\delta V_s)|}{\phi(1-R)}\cdot\left(1+\left[\frac{Re(\delta V_s)}{Im(\delta V_s)}\right]^2\right)$$

7   where $\phi(1-R)$ is the intensity of light absorbed in the

8   semiconductor, q is the elementary charge, and ϵ_s is the

9   semiconductor permittivity.

10   In addition to the space-charge capacitance, C_{sc}, the

11   measurement of the surface photovoltage can be used to determine

12   the surface charge density, Q_{ss} , the doping concentration, N_{sc} , and

13   the surface recombination lifetime, τ, using the following

14   relationships. The space charge capacitance, C_{sc}, is proportional

15   to the reciprocal of the semiconductor depletion layer width, W_d,

16   according to the relationship:

$$C_{sc} = \frac{\epsilon_s}{W_d}$$

17   where ϵ_s is the semiconductor permittivity. The density of

18   space charge, Q_{sc}, is in turn described by equation:

19    $$Q_{sc} = q\,N_{sc}W_d$$

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1   where q is an elementary charge and the net doping

2   concentration in the space-charge region, N_{sc}, is positive in an n-

3   type material and negative in a p-type material. In addition,

4   since the surface charge density, Q_{ss}, is given by the expression:

5 $$Q_{sc} = - Q_{ss}$$

6   the surface charge density is easily determined from the space

7   charge density.

8   Further, if an inversion layer can be created at the wafer

9   surface, the depletion layer width, W_d, under inversion conditions

10   is related to the net doping concentration, N_{sc} , according to the

11   relationship:

$$W_d = \sqrt{\frac{4\epsilon_s kT \ln(|N_{sc}|/n_i)}{q^2 |N_{sc}|}}$$

12   where kT is the thermal energy and n_i is the intrinsic

13   concentration of free carriers in the semiconductor. Several

14   methods of forming such an inversion layer at the semiconductor

15   surface are disclosed below.

16   Finally, the surface recombination rate may also be determined

17   from the SPV. The recombination lifetime of the minority carriers

18   at the surface, τ, is given by the expression:

$$\frac{1}{\omega\tau} = \left| \frac{Re(\delta V_s)}{Im(\delta V_s)} \right|$$

1   In brief overview, and referring to Fig. 1, an embodiment of

2   such an apparatus 10 for the real-time, in-line, electrical

3   characterization of a semiconductor during manufacturing using

4   induced surface photovoltage includes a sensor probe assembly 14,

5   supporting electronics 18, and a wafer conveying device 22. In

6   operation, the wafer conveying device 22, such as a conveyor belt,

7   a robotic arm, a wafer chuck or similar device, moves wafers 28,

8   28' through the manufacturing process and, in one embodiment,

9   beneath the sensor head assembly 14.

10   Referring to Fig. 2, the sensor probe head assembly 14

11   includes a probe head 32 mounted in a bracket 36 on a motorized

12   stage 40. The motorized stage 40 moves the probe head 32 in a

13   vertical direction (arrow z) to adjust vertical position of the

14   probe head 32 with respect to the wafer 28 to within a 0.2 μm

15   accuracy. The mechanical stage 40 is attached to a probe arm 44.

16   The longitudinal axis L-L' of the probe head 32 is adjusted to

17   be perpendicular to the plane of the wafer 28, by adjusting the

18   tilt of the probe arm 44, either manually (using set screws 46) or

19   mechanically (using for example piezoelectric actuators 48). The

20   vertical position of the probe head 32 with respect to the wafer 28

21   is controlled by feedback signal from capacitive-position sensing

22   electrodes described in detail below.

23   Briefly, three capacitive-position sensing electrodes are

24   located on the periphery of the sensor. To measure capacitance

25   between each of these electrodes and the wafer, a 70 kHz 1V signal

26   is applied through a respective 10 kohm resistor connected to each

27   of these electrodes. The AC current flowing through these

1   resistors in measured using a preamplifier and a lock-in amplifier.

2   The lock-in signal is further processed by a computer and supplied

3   to the motion control board that, in turn, positions the probe at

4   a predetermined distance from the wafer surface using vertical (z-

5   axis) motorized stage.

6   Referring to Fig. 3, the probe head 32 includes a sensor mount

7   assembly 50 which provides support for a sensor 54 that is

8   connected to a preamplifier board 58 by a plurality of flexible

9   connectors 60. Light emitted by a light emitting diode (LED) 64 is

10   collimated by lens 68 prior to passing through a beam splitter 72.

11   LED 64 is mounted on a LED driver board 74 which controls the

12   intensity of the LED 64, in response to a signal from a reference

13   photodiode 78, (through a preamplifier 79) at an intensity level

14   determined by the computer 160. Light from the LED 64 reaches the

15   reference photodiode 78 by being partially reflected by the beam

16   splitter 72. The light which passes through the beam splitter 72

17   passes through openings 80, 82 in the circuit board 86 and the

18   preamplifier board 58, respectively, prior to passing through the

19   sensor mount assembly 50 and impinging on the wafer 28 undergoing

20   testing.

21   Light reflected by the wafer 28 passes back along the light

22   path just described before being reflected by the beam splitter 72

23   to a measuring photodiode 92. The light reflected by the wafer 28,

24   Φ_R, is used to detect edge of the wafer passing beneath the probe

25   head 32 and trigger measurements. The reflected light is also used

26   to measure light absorbed in the wafer 28 according to the

27   relationship:

$$\Phi = \Phi_0 - \Phi_R$$

1

2 where Φ_0 is the incident light which can be determined by

3 measuring the light reflected from an aluminum mirror replacing

4 the wafer 28. In this way, the reflection coefficient of the

5 wafer 28 can be determined. Although the above embodiment

6 describes the splitting of light by a beam splitter, other

7 embodiments are possible in which light is split using optical

8 fibers.

9 Referring again to Fig. 1, the LED 64 is controlled by signals

10 from, and the probe head 32 returns signals to, supporting

11 electronics 18. The supporting electronics 18 include an

12 oscillator 100 which supplies a 40 kHz modulation control

13 signal 104 that is used as a reference signal by an LED control 62

14 to control an LED driver 63 which powers the LED 64. Oscillator

15 100 also provides a reference signal 108 to a lock-in amplifier

16 112. The output signals 116 from the surface photovoltage sensor

17 and the measurement photodiode 92 (through a preamplifier 93) of

18 the probe head 32 are input signals to multiplexer 120 that

19 alternately connects each signal to the input of the lock-in

20 amplifier 112. The lock-in amplifier 112 demodulates the input

21 signal and supplies the demodulated signal to another multiplexer

22 150. Multiplexer 150 switches between the two input signals from

23 lock-in amplifiers 112 and 140 connecting them to a data

24 acquisition (DAQ) board 156 that in turn digitizes the input

25 signals making them available for further processing in the

26 computer 160. In an alternate embodiment, multiplexer 150 is part

27 of the data acquisition board 156.

1   Fig. 4 is a bottom perspective view showing the sensor plate

2   of the sensor head 32. A plurality of electrodes are formed on a

3   rigid and insulating substrate 200. In one embodiment, a 10mm

4   diameter fused quartz disc is used.   A central surface

5   photovoltage electrode 204 detects the signal from the wafer 28.

6   The central surface photovoltage electrode 204 is partially

7   transmissive, thereby permitting the light from the LED 64 to reach

8   the wafer 28. Three other electrodes 208 located on the periphery

9   of the substrate are used both for sensing the position of the

10   sensor head 32 above the wafer 28 and for measuring the parallelism

11   of the sensor with respect to the surface of the wafer 28. All

12   electrodes 204, 208 are formed by the deposition of an indium-tin-

13   oxide film through a shadow mask.

14   Similarly, a plurality of electrodes 212, for connecting the

15   sensors with the preamplifier circuit board 58 through the flexible

16   connectors 60, are formed on the surface of the substrate 200 which

17   is opposite the electrodes 204, 208. Thin conductive electrodes

18   218, on the side walls of the substrate 200, which connect the

19   electrodes 204, 208 on the first surface with their respective

20   electrodes 212 on the second surface, are also deposited using a

21   shadow mask. This deposition avoids the use of vias through the

22   substrate and thereby retains the flatness of the sensor to better

23   than $.2\mu$m. Both front 204, 208 and side electrodes 218, may be

24   protected with a thin insulating coating, such as polyimide, formed

25   by spinning so as to maintain the flatness of the sensor.

26   The electrodes 208 are used for capacitively sensing the

27   position of the sensor above the wafer 28. Referring again to

1 Fig. 1, a 70 kHz input signal 124 for measuring the distance from

2 a wafer 28 is supplied by an oscillator 128 to the position

3 electrodes 208. The same signal is also supplied as a reference

4 signal 132 for a lock-in amplifier 140. A position signal 146 from

5 each of the three position sensing electrodes 208 is supplied as

6 the input signal to a multiplexer 148 through a preamplifier 149.

7 The multiplexer 148 in turn, switching between each of these

8 signals, connects each alternately to a lock-in amplifier 140. The

9 demodulated output signals from the lock-in amplifiers 112 and 140

10 are input signals to a multiplexer 150 which connects each signal

11 alternately to a data acquisition board 156 located in a

12 computer 160, including a CPU 164. Again, in an alternative

13 embodiment, multiplexer 150 is part of the data acquisition

14 board 156.

15 The position signal 146 is compared by the CPU 164 with the

16 reference value corresponding to a desired distance (established by

17 calibration and stored in the computer) between the sensor 54 and

18 the wafer 28. The difference between these two values, corresponds

19 to the deviation of the sensor-wafer distance from the desired

20 value, is supplied to a motion control board 170 that positions the

21 probe head 32 at a predetermined distance from the wafer 28 using

22 the motorized stage 40.

23 In operation, when an edge of the continuously moving wafer 28

24 crosses the beam of the intensity modulated light from LED 64, the

25 intensity of the reflected light increases, thereby increasing the

26 signal from the photodiode 92. This measurement of the reflected

27 light is repeated and the new value compared with the previous

1   value.   The light intensity measurements are repeated until the

2   difference between sequential values decreases to below 5%

3   indicating that the entire light beam is within the flat portion of

4   the wafer.

5   This decrease in deviation triggers acquisition of the SPV

6   signal by the surface photovoltage electrode 204, followed by

7   acquisition of the capacitance signals by the position

8   electrodes 208. If capacitance signals from different electrodes

9   (208) differ by more than 5%, the SPV signal is stored but not

10 recalculated.   The sequence of all measurements is then repeated

11 until capacitances from different position electrodes (208) fall

12 within 5% limit indicating that the electrodes are not near the

13 edge of the wafer 28.   The average of the capacitances from the

14 three positioning electrodes 208 at this point is used to

15 recalculate all previous values of the SPV signal.

16   The SPV measurement cycle is repeated, sequentially measuring

17 light intensity, SPV signal and capacitance of positioning

18 electrodes, until capacitances from the three positioning

19 electrodes (208) differ by more than 5%, indicating the approach of

20 the opposite edge of the wafer 28. After reaching this point of

21 the wafer 28, the SPV measurements are made using the previously

22 measured values of capacitance.   The measurements of each value

23 (reflected light, SPV signal, capacitance), in each cycle, are

24 repeated for 10 msec and averaged by CPU 164.

25   The wafer 28, in one embodiment, is placed on the grounded

26 chuck (conveyor belt, robotic arm, or other similar device) 178,

27 coated with an insulating material, that is used to carry   the

- 15 -

1   wafer 28 beneath, above, or otherwise, such that the surface of the

2   sensor of the probe head 32 and the surface of the wafer are

3   parallel. Alternatively, the conveying device may be biased by a

4   DC voltage. In one embodiment the DC bias voltage is selected to

5   be between -1000 and 1000 volts. Although Fig. 1 illustrates the

6   use of a grounded, insulated chuck 22 to move the wafer 28 beneath

7   the probe assembly 14, it is possible to provide all the necessary

8   measurements without grounding the chuck using only the electrodes

9   provided by the sensor 54. Referring to Fig. 5, the SPV signal is,

10   as described previously, received by the central surface

11   photovoltage electrode 204 which is connected to the input terminal

12   of an operational amplifier 250 located on the preamplifier circuit

13   board 58. The other input terminal of the operational

14   amplifier 250 is connected to ground and to the output terminal of

15   the operational amplifier 250 through one or more resistors. What

16   was previously a back capacitive contact, supplied by the chuck, is

17   now provided by the three positioning electrodes 208 located on the

18   periphery of the sensor and which, during the SPV measurements, are

19   connected to the ground 252 rather than to the input terminal of

20   the capacitance (current measuring) preamplifier located on the

21   preamplifier circuit board 58.

22   To measure capacitance, the electrodes 208 are alternatively

23   switched between the ground 252 and input of the capacitance

24   preamplifier located on preamplifier circuit board 58. This

25   arrangement makes possible non-contact measurements with any type

26   of wafer support. Thus, the wafer support does not need to be

27   connected to ground and could be made of insulating material.

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1   As discussed above, measurements of the surface doping

2 concentration require the formation of an inversion layer at the

3 wafer surface. In one embodiment this is accomplished by charging

4 the wafer 28 using a corona generator and subsequently performing

5 surface photovoltage measurement on the wafer 28. Specifically,

6 the wafer 28 is first charged to inversion with a corona generator.

7 N-type wafers require a negative surface charge and p-type wafers

8 require a positive surface charge. In one embodiment, the corona

9 generator includes a single metal tip, for example tungsten,

10 located 5mm above the wafer 28 and biased to 3.5kV for 2 to 3 sec.

11 After charging, the wafer 28 is moved beneath the probe assembly 14

12 and the measurements performed. After the measurement, the

13 wafer 28 is either moved beneath a neutral charge corona generator

14 or returned to the original corona generator operated in a neutral

15 discharge mode in order to discharge the wafer.

16   The simple corona generator with the metal tip or wire does

17 not allow for the controlled charging of the wafer surface. The

18 control of charging is important because while there is a minimum

19 charge required to induce an inversion layer at the wafer 28

20 surface, overcharging may damage the wafer surface, and even cause

21 electrical breakdown of the insulating coating formed on the wafer

22 surface. To avoid overcharging the wafer 28, a closed loop

23 controlled corona charging arrangement, disclosed in Figs. 6a and

24 6b, controls the charge deposited on the surface of the wafer and

25 thereby prevents surface damage.

26   Referring to Fig. 6a, the wafer 28 on the grounded, insulated

27 chuck 22 is moved beneath an ionized air source 260 located about

- 17 -

1   10mm above the wafer 28. A mesh, stainless-steel, reference

2   electrode 264 is placed in a distance of about 0.5 mm to 1mm from

3   the wafer 28. The difference between the potential on the

4   reference electrode 264, V_{el}, and a user defined and computer

5   generated reference voltage, V_{ref}, 268, termed the differential

6   potential, V_{diff}, is amplified and its polarity is reversed within the

7   corona control module 270. This voltage, V_{corr}, is applied to the

8   ionized air source 260. Thus, the polarity of the potential

9   applied to the ionized air source 260, V_{corr}, by the corona control

10 module 270 is opposite to the polarity of differential voltage and

11 is given by the expression:

$$V_{corr} = V_{ref} - V_{el}$$

13 Control of the corona charging during the charging process

14 allows not only for real-time control but allows also simpler

15 electronic circuitry to be used. The presence of the ions between

16 ionized air source 260, reference electrode 264, and the wafer 28

17 lowers the equivalent impedances in the circuity and permits

18 amplifiers to be used (in the control module 270) which have an

19 input impedance of 10^9 - 10^{10} ohms. This input impedance is several

20 orders of magnitude lower than in the amplifiers utilized in

21 previous approaches (typically 10^{13} - 10^{15} ohms) when a potential of

22 the wafer surface is measured not during charging but after the

23 turning off of the corona.

24 Referring to Fig. 6b, the wafer 28 may be discharged by

25 setting the reference voltage 268 to zero, i.e., connecting it to

26 ground. Alternatively, if separate corona units are used for

- 18 -

1   charging and discharging of the wafers, the discharging corona

2   reference voltage can be permanently attached to the ground.

3   Referring to Fig. 7, an alternative approach to inducing a

4   surface inversion layer is to bias the sensor with a high voltage.

5   Such an approach requires formation of the insulating film 230 such

6   as polyimide over the central electrode 204 and positioning

7   electrodes 208 of the sensor. Fig. 8 depicts this alternative

8   approach to inducing an inversion layer at the surface of the wafer

9   28 by voltage biasing. Fig 8 shows a schematic diagram of an

10   electronic circuit that includes a preamplifier for measuring AC

11   surface photovoltage and a connection to a biasing high voltage

12   source used with the sensor having a polyimide coating 230 as just

13   described. The insulating coating 230 of the sensor 54 allows the

14   application of a high enough voltage (500-1000 V) to induce a

15   surface inversion layer in typical wafers used in manufacturing.

16   The arrangement in which a rigid sensor electrode 204 is separated

17   by an air gap from the semiconductor surface requires high degree

18   of flatness of the electrode surface. When such a high DC voltage

19   is used, any edges or surface roughness will increase the local

20   electrical field and enhance ionization of the air resulting in

21   electrical breakdown. Therefore electrical connections between the

22   electrode and the detection electronics are constructed so as to

23   have a minimal effect on the surface flatness. Thus, the use of

24   the side connections 218 eliminates the need to form via holes in

25   the sensor and maintains the high flatness of the sensor. The

26   current in the space charge region of the wafer 28 (indicated in

27   phantom) which is generated by the illumination of the wafer 28 by

- 19 -

1 the LED 64 is depicted as an equivalent current source, J_h. An

2 equivalent resistor, R_R, which represents the carrier

3 recombination at the surface of the wafer 28 and an equivalent

4 capacitor, C_{SC}, which represents the space charge capacitance are

5 also depicted. C_G represents capacitance between the wafer 28 and

6 the chuck 22, while C_P represents capacitance between the sensor

7 electrode 204 and the wafer 28. A computer controllable high

8 voltage 300 is applied through a 10 Mohm resistor, R_{HV}, to the

9 sensor electrode 204. The sensor electrode 204 is also connected

10 to the input of the operational amplifier 250 (described

11 previously) through a high voltage capacitor, C_{HV}. The capacitance,

12 C_{OA}, (also shown in phantom) represents input capacitance of the

13 operational amplifier 250. C_{HV} is selected to be about 10 times

14 larger than C_{OA} so that C_L used in calculating $Im(\delta V_s)$ and $Re(\delta V_s)$ is

15 close to C_{OA}. Similarly R_L used in calculating $Im(\delta V_s)$ and $Re(\delta V_s)$

16 is close to R_{HV}.

17 In addition to the methods just described to form an inversion

18 layer, an inversion layer at the surface of the wafer 28 can be

19 also formed using a chemical treatment. This approach is

20 especially useful for p-type silicon wafers. Since HF introduces

21 positive surface charge, HF treatment will produce a negative

22 inversion layer at the surface of p-type silicon wafers. In one

23 embodiment, the silicon wafer to be tested is subjected to a

24 mixture of hydrofluoric acid and water (1:100 $HF:H_2O$) in a liquid

25 or vapor form. The wafer is then placed beneath the probe

26 assembly 14. In number of processes, HF treatment is already part

- 20 -

1 of the production sequence so that probe assembly 14 needs only to

2 be placed after HF processing location.

3 It should be noted that the formation of an inversion layer is

4 useful in measuring conductivity type.

5 Since, in some cases, incoming wafers show acceptor

6 neutralization due to the presence of hydrogen or copper, in order

7 to restore the doping concentration at the surface, the measured

8 wafer is subjected to a high intensity illumination (e.g., using a

9 250W halogen light source) after a SPV measurement is made.

10 Additionally, the present apparatus is particularly adaptable

11 for use in a sealed chamber environment, such as a reduced pressure

12 chamber, a chamber for chemically reactive gasses or a chamber for

13 an inert environment. The entire probe assembly 14 may be

14 positioned within the sealed chamber, with the connections to the

15 electronics passing through the walls of the sealed chamber through

16 pressure fittings. Alternatively, the probe assembly may be

17 mounted in a wall of a sealed chamber such that the sensor is

18 positioned within the chamber but the remainder of the probe

19 assembly is positioned outside of the sealed chamber.

20 The approach to process monitoring methodology using an AC-SPV

21 method emphasizes determination of variations of the measured

22 parameters from wafer to wafer rather than value of the specific

23 parameter itself. Typically, measurements of the electrical

24 parameters of the back surface of the wafer are not possible

25 without altering the front surface, which has to be contacted in

26 order to complete a measuring circuit. Hence, measurements

27 performed on the back surface of the wafer are not typically used

1 in process monitoring. The non-contact AC-SPV measurements allows

2 process monitoring by measurement of the surface characteristics on

3 the back surface of the wafer as well as the front surface. As

4 described before, the probe head can be installed underneath the

5 wafer, above the wafer, or otherwise, such that the sensor surface

6 is parallel to the wafer back surface, depending on how the wafer

7 conveying system conveys the wafer to the probe head. In addition,

8 two probe heads can be used, one on each side of the wafer for

9 simultaneous characterization of the front and back side of the

10 wafer. As an illustration of such approach comparison of

11 measurements of the surface charge on the front surface featuring

12 mirror-like finish is shown in Fig. 9. The measurements were

13 performed on the two halves of the same 100mm, p-type, (100)

14 silicon wafers that were simultaneously subjected to the wet

15 cleaning treatments. At various stages of the cleaning process,

16 the surface charge was measured on the front (polished) surface of

17 one half, and on the back (unpolished) surface of the other half.

18 The results shown in Fig. 9 indicate identical behavior of surface

19 charge on the front and back surfaces.

20 Having shown the preferred embodiment, those skilled in the

21 art will realize many variations are possible which will still be

22 within the scope and spirit of the claimed invention. Therefore,

23 it is the intention to limit the invention only as indicated by the

24 scope of the following claims.